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Investigation of convection control under the non-uniform RMF in a liquid bridge

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Abstract

Under microgravity, thermocapillary flow becomes the dominant convection in float-zone crystal growth, it may lose stability with increasing Marangoni number, and the convection instability is detrimental to crystal quality. Because of the excellent electrical conductivity of semiconductor melt, the external rotating magnetic field (RMF) is applicable to control melt convection. In a typical simplified float-zone model, the influences of the non-uniform RMF, which is generated by the RMF inductor with three pairs of poles, on the three-dimensional thermocapillary flow are investigated numerically. Our results demonstrate that the axial velocities are reduced under the non-uniform RMF while the melt is stirred in azimuthal direction by RMF, as a result, the three-dimensional convection after the instability becomes to a two-dimensional axisymmetrical flow. It implies that the non-uniform RMF can control melt convection effectively for high-quality crystal growth.

Keywords: Rotating magnetic fields, thermocapillary convection, floating zone, Marangoni convection, microgravity;

1. INTRODUCTION

The float-zone crystal growth technology is a containerless method, which makes it possible to grow high purity crystal. Under microgravity, the float-zone method can avoid the influence of gravity field and

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break the limitation of crystal size, and a large and high quality single crystal may be achieved. While the buoyancy flow is minimized under microgravity, thermocapillary flow driven by the unbalanced surface tension becomes dominant in float-zone and plays an important role in heat and mass transfer. Thermocapillary flow may lose stability with the increase of temperature gradient and floating zone size, which has deleterious effect on crystal quality [1,2]. Since semiconductor melt is of excellent electrical conductivity, an external rotating magnetic fields (RMF) is a potential choice to control melt convection and therefore, to improve grown crystal quality.

Dold and Benz [3], Gelfgat et al. [4], and Witkowski and Walker [5] demonstrated that the external RMF can effectively control the convection and temperature fields in the semiconductor melt. The uniform RMF (p=1, here p is the number of pole pair of the RMF inductor) was usually applied in the float-zone. With a two-dimensional axisymmetric model, Witkowski and Walker [5] investigated the competition between convection driven by the uniform RMF and convection caused by the unbalanced surface tension. Dold et al. [6] found that a time-dependent three-dimensional flow changed to a quasi-axisymmetric flow under uniform RMF in float-zone model. So far, however, the effect of the non-uniform RMF on the melt convection in the float-zone is seldomly investigated. To better understand the convection control of the non-uniform RMF, the effect of the applied RMF (p=3) on the thermocapillary flow is simulated numerically in the present paper.

2. PHYSICAL MODEL AND BASIC EQUATIONS

2.1 Physical model

The floating liquid bridge model, a cylindrical liquid bridge suspended between two disks with different temperatures T_{top} =0 and T_{bottom} =1 as shown in Fig.1(a), is a typical simplified model of float-zone, and the main convection characteristics in float-zone can be well captured in this liquid bridge model, therefore the liquid bridge model is widely adopted[7-10]. In the paper, the aspect ratio of the liquid bridge, which is defined as the ratio of height to radius As:=H/R , is taken as 1. The non-uniform RMF (p=3) described in the Cartesian coordinate system is:

$$\begin{aligned}\dot{B}_{rot}(x,y,t) = \frac{B_0}{R^2}[&-\dot{e}_x((x^2-y^2)\cdot sin(3\omega t)-2x\cdot y\cdot cos(3\omega t)) \\ &+\dot{e}_y((x^2-y^2)\cdot cos(3\omega t)+2x\cdot y\cdot sin(3\omega t))]\end{aligned}, \qquad (1)$$

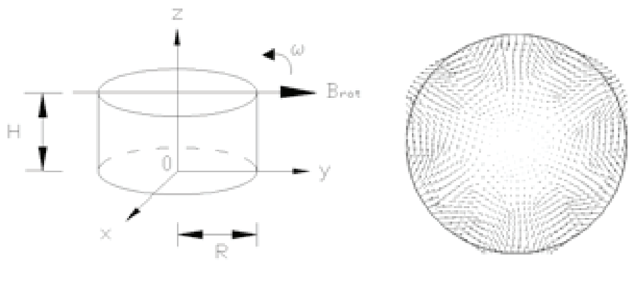


Fig.1 (a) The liquid bridge model and (b) plan form of magnetic lines for the non-uniform RMF (p=3)

thereinto, B_0 is the amplitude of RMF, ω ($\omega=2\pi\cdot\lambda$) is the angular frequency, and $\bar{e}_x$, $\bar{e}_y$ are unit vectors in the x and y directions, respectively. The amplitude of non-uniform RMF is 7mT and its rotating frequency λ is 50Hz. The magnetic lines of non-uniform RMF (p=3) are assumed to permeate the whole melt zone without change, and its planform is shown in Fig.1(b).

2.2 Dimensionless governing equations

The semiconductor melt is considered to be incompressible Newton fluid with constant viscosity and density. The free surface is idealized to be adiabatic from the environmental gas. The governing equations for melt convection in the non-uniform RMF are nondimensionalized, and the corresponding characteristic scales of length, velocity, time, pressure and electric potential are H, k/H, H^2/k, $k\mu/H^2$, B_0k, respectively. The dimensionless governing equations take the form:

$$\nabla\cdot\vec{U}^* = 0 \ ;$$

$$\frac{1}{Pr}\left(\frac{\partial\vec{U}^*}{\partial t^*} + (\vec{U}^*\cdot\nabla)\vec{U}^*\right) = -\nabla P^* + \Delta\vec{U}^* + 2Ta\,Pr\,\vec{F}^*_{rot} - \vec{F}^*_s\delta(r^* - R^*(z^*)) \ ; \qquad (2)$$

$$\frac{\partial T^*}{\partial t^*} + (\vec{U}^*\cdot\nabla)T^* - \nabla^2 T^* = 0 \ ;$$

The Prandtl, magnetic Reynolds, Marangoni and Taylor numbers are defined as:

$$Pr = \frac{\upsilon}{k}, \ Re_\omega = \frac{\omega H^2}{\upsilon}, Ma = \frac{\sigma_k \Delta TH}{\rho\upsilon k}, Ta = \frac{\sigma_e B_0^{\,2}\omega H^4}{2\upsilon\mu},$$

where, the dimensionless temperature is $T^* = \left(T - T_{top}\right)/\Delta T$ with $\Delta T = T_{top} - T_{bottom}$, k stands for the thermal diffusivity, μ viscosity, σ_k the surface tension coefficient, σ_e the electrical conductivity, δ the Kronecker operator. $\vec{F}^*_s\delta(r^* - R^*(z^*))$ represents that the surface tension only acts on the free surface, r^* is $r^* = \sqrt{x^{*2} + y^{*2}}$, R^* is the radius of the free surface, and

$$\vec{F}^*_s = Ma\left[\frac{\partial T^*}{\partial x^*}\vec{e}_x + \frac{\partial T^*}{\partial y^*}\vec{e}_y + \frac{\partial T^*}{\partial z^*}\vec{e}_z\right].$$

"*" is neglected in the paper for the sake of convenience. Applying the basic idea for $\phi_1 - \phi_2$ model of the uniform RMF [10], the components of the dimensionless Lorentz force are derived as:

$$f_x = \frac{1}{Re_\omega\cdot Pr}\left[\frac{\partial\phi_1}{\partial z}xy + \frac{\partial\phi_2}{\partial z}\frac{x^2-y^2}{2} - u_x\left(\frac{(x^2-y^2)^2}{2} + 2x^2y^2\right)\right] + \left(-y\left(\frac{(x^2-y^2)^2}{2} + 2x^2y^2\right)\right) \ ; \qquad (3.1)$$

$$f_y = \frac{1}{Re_\omega\cdot Pr}\left[\frac{\partial\phi_1}{\partial z}\frac{x^2-y^2}{2} - \frac{\partial\phi_2}{\partial z}xy - u_y\left(\frac{(x^2-y^2)^2}{2} + 2x^2y^2\right)\right] + \left(x\left(\frac{(x^2-y^2)^2}{2} + 2x^2y^2\right)\right) \ ; \qquad (3.2)$$

$$f_z = \frac{1}{Re_\omega\cdot Pr}\left[-\left(\frac{\partial\phi_1}{\partial y} + \frac{\partial\phi_2}{\partial x}\right)\frac{x^2-y^2}{2} - \left(\frac{\partial\phi_1}{\partial x} + \frac{\partial\phi_2}{\partial y}\right)xy - u_z\left((x^2-y^2)^2 + 4x^2y^2\right)\right]. \qquad (3.3)$$

Dimensionless equations of the electrical potential are derived as:

$$\nabla^2\phi_1 = -\left(\frac{\partial u_z}{\partial x}2xy + \frac{\partial u_z}{\partial y}(x^2-y^2) - \frac{\partial u_x}{\partial z}2xy - \frac{\partial u_y}{\partial z}(x^2-y^2)\right) \ ; \qquad (4.1)$$

$$\nabla^2\phi_2 = -\left(\frac{\partial u_z}{\partial x}(x^2-y^2) - \frac{\partial u_z}{\partial y}2xy - \frac{\partial u_x}{\partial z}(x^2-y^2) + \frac{\partial u_y}{\partial z}2xy\right) \ . \qquad (4.2)$$

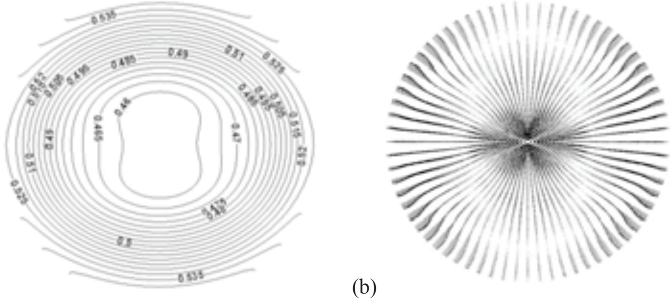
All the boundaries are assumed to be electric insulation, so the equations of the electrical potential on the boundary are derived as：

$$\frac{\partial\phi_1}{\partial n} = \left[-2xy\cdot w\cdot\dot{e}_x - w(x^2-y^2)\cdot\dot{e}_y + \left(2xy\cdot u + (x^2-y^2)\cdot v + (2xy^2 - x^3 + xy^2)\cdot Re_\omega\,Pr\right)\dot{e}_z\right]\cdot\dot{n} \ ;$$

$$\frac{\partial \phi_2}{\partial n} = [-(x^2 - y^2)\cdot w \cdot \dot{e}_x + 2xy \cdot w \cdot \dot{e}_y + \left((x^2 - y^2)\cdot u - 2xy \cdot v + (x^2 y - y^3 + 2x^2 y)\cdot Re_\omega \, Pr\right)\dot{e}_z \,] \cdot \dot{n}\,.$$

The velocity boundary conditions for top and bottom disks are taken as $\vec{U} = 0$, the corresponding temperature boundary conditions are T_{top}=0 and T_{bottom}=1, respectively; the surface tension is introduced directly into N-S equation as in eq.(2), and therefore the boundary condition for the free surface is takes as impervious to flow of mass, momentum and energy.

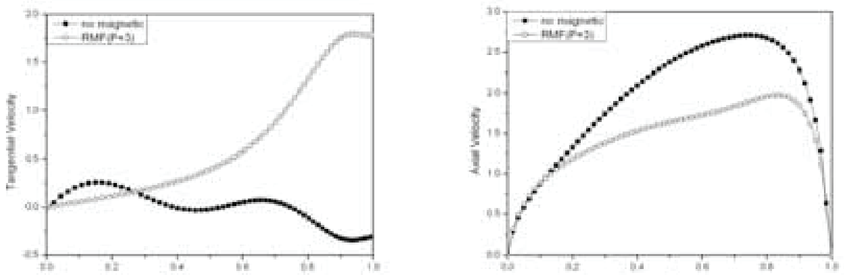
3. ANALYSIS AND CONCLUSION



(a) (b)

Fig.2 (a) Temperature contours and (b) velocity vectors at z=0.5 without magnetic field for Ma=30

Without magnetic field, the two-dimensional axisymmetric steady melt convection loses stability to become three-dimensional when Ma is increased to exceed the critical Marangoni number. For thermocapillary flow in liquid bridge with Ma=30 and As=1, a 2-fold convection structure is observed as in Figs. 2(a) and 2(b).



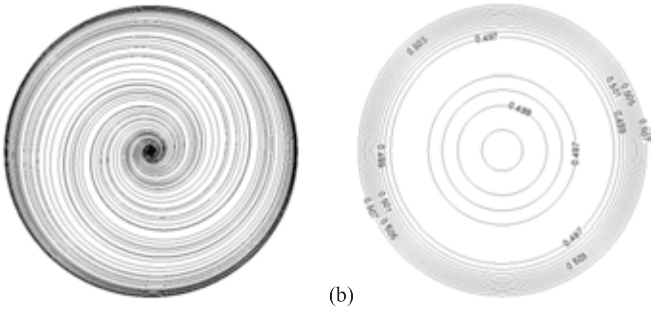
(a) (b)

Fig.3 (a) Tangential velocity component along line from point (0,0,0.5) to point (1,0,0.5) and (b) axial velocity component along line from point (1,0,0) to point (1,0,1) with and without non-uniform RMF (p=3)

Because of the Lorentz force, it is possible to control the convection of the semiconductor melt by applying an external non-uniform RMF. In transversal non-uniform RMF, the Lorenz force stirs the melt in the azimuthal direction on the one hand, and it also suppresses the convection in the axial direction on the other hand. Comparing with the azimuthal velocity without magnetic field, the azimuthal velocity in the melt increases greatly under the non-uniform RMF (p=3), and it reaches the maximal value near the free surface as shown in Fig.3 (a). Meanwhile, the maximal axial velocity under the non-uniform RMF (p=3) is

27% smaller than that without magnetic field, and the axial velocity is suppressed effectively as shown from Fig.3 (b).

The electromagnetic stirring action of the RMF is helpful to eliminate non-axisymmetric disturbance, and the axial convection induced by the unbalanced surface tension is also suppressed effectively in the non-uniform RMF (p=3), which all are beneficial for the three-dimensional thermocappillary convection to become axisymmetric one. As shown in Fig.4, the three-dimensional steady thermocappillary convection for Ma=30 without magnetic field is well controlled to become a two-dimensional axisymmetric steady flow under the non-uniform RMF. The results indicate that the non-uniform RMF (p=3) is a potential effective method to control convection to grow high-quality semiconductor crystal in float-zone under microgravity.



(a) (b)

Fig.4 (a) Streamlines and (b) temperature contours at z=0.5 in the non-uniform RMF (p=3) for Ma=30

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